Fuel Processing Technology 157 (2017) 108–115

Contents lists available at ScienceDirect

Fuel Processing Technology

journal homepage: www.elsevier.com/locate/fuproc

Research article

Combustion, performance and emission analysis of a DI diesel engine using plastic pyrolysis oil

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ARTICLE INFO

Article history:
Received 13 October 2016
Received in revised form 29 November 2016
Accepted 30 November 2016
Available online 14 December 2016

Keywords:
Plastic pyrolysis oil
Diesel engine
Combustion
Performance
Emissions

ABSTRACT

Plastic waste is an ideal source of energy due to its high heating value and abundance. It can be converted into oil through the pyrolysis process and utilised in internal combustion engines to produce power and heat. In the present work, plastic pyrolysis oil is manufactured via a fast pyrolysis process using a feedstock consisting of different types of plastic. The oil was analysed and it was found that its properties are similar to diesel fuel. The plastic pyrolysis oil was tested on a four-cylinder direct injection diesel engine running at various blends of plastic pyrolysis oil and diesel fuel from 0% to 100% at different engine loads from 25% to 100%. The engine combustion characteristics, performance and exhaust emissions were analysed and compared with diesel fuel operation. The results showed that the engine is able to run on plastic pyrolysis oil at high loads presenting similar performance to diesel while at lower loads the longer ignition delay period causes stability issues. The brake thermal efficiency for plastic pyrolysis oil at full load was slightly lower than diesel, but NO_X emissions were considerably higher. The results suggested that the plastic pyrolysis oil is a promising alternative fuel for certain engine application at certain operation conditions.

1. Introduction

Global warming, waste policies and fossil fuels' unstable price have forced a focus on developing alternative energy sources in order to cover energy demand and replace fossil fuels. The alternative energy sources that are mostly used are hydropower, solar energy, wind energy, geothermal energy, nuclear energy, biomass and wastes. A type of waste that is in plentiful supply and can be used effectively as energy is waste plastic. Over the last three decades the production of plastic has faced an explosive growth and reached the 129 million tonnes per year [1]. Synthetic polymers production such as polyethylene (PE), polypropylene (PP), polystyrene (PS) and polyvinyl chloride (PVC) has increased dramatically in the last 30 years. All the plastic that is produced should be managed efficiently at its end of life to avoid further pollution of the environment caused by landfilling or incinerating waste plastics. In recent years, despite many environmentally friendly ways being developed in order to recycle the waste plastics, millions of tonnes are dumped everyday instead of being recycled [2].

Conversion of waste plastics into fuel is deemed a promising solution since they are energy rich. It can be achieved by conventional refinery processes such as pyrolysis, gasification, hydrocracking, catalytic cracking and others. One of the most promising technologies is the pyrolysis process [3,4]. Pyrolysis is a thermal degradation process that occurs in the absence of oxygen. Waste plastics can be broken down through the pyrolysis process into three products; liquid, gas and solid (small amount). The pyrolysis product's quality depends on the waste plastic type that feeds the pyrolysis reactor and the process parameters (such as temperature, residence time and catalyst) [5–8]. The liquid product, i.e. plastic pyrolysis oil (PPO) has similar properties to petroleum products therefore has the potential to be used in internal combustion engines. Nowadays, significant research has been focused on diesel engines because of the great driveability and the high efficiency over a broad load range. Despite the fact that diesel engines produce a significant amount of NO_X and PM emissions, they are experiencing rapid growth. As a result, the search for alternative fuels to replace the petroleum diesel is considered essential.

Up until now, little research has been conducted on the use of plastic pyrolysis products in diesel engines. It is difficult to compare the engine performance between different investigations as the oil quality is not the same due to the different plastic type feedstock

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http://dx.doi.org/10.1016/j.fuproc.2016.11.016

Nomenclature

PPO	plastic pyrolysis oil
PPO 25	25% plastic pyrolysis oil + 75% diesel fuel
PPO 50	50% plastic pyrolysis oil + 50% diesel fuel
PPO 75	75% plastic pyrolysis oil + 25% diesel fuel
PPO 90	90% plastic pyrolysis oil + 10% diesel fuel
PPO 100	100% plastic pyrolysis oil
NO_X	nitrogen oxides
PM	particulate matter
CO	carbon monoxide
CO_2	carbon dioxide
HC	hydrocarbon
LHV	lower heating value
BMEP	brake mean effective pressure
HRR	heat release rate
ϕ	equivalence ratio
BSFC	brake specific fuel consumption
BTE	brake thermal efficiency

and pyrolysis process. However, the core research has been focused on the use of PPO in blends with diesel in a single-cylinder diesel engines [2,9-13]. Furthermore, in larger diesel engines the use of PPO blends with diesel has been investigated by J. Pratoomyod et.al, but without analysing the combustion performance [14]. These investigations showed that the engine can tolerate a medium blend rate but with lower engine performance and higher NO_X, CO and UHC emissions in comparison with diesel operation. What has not been investigated yet in larger diesel engines is the use of the PPO at high blend rates and without diesel, and the analysis of the combustion performance. The purpose of this study is to evaluate the feasibility of utilising plastic pyrolysis oil as an alternative diesel engine fuel and estimate the best operational conditions. To fulfil this purpose, the oil properties were fully analysed, and its engine performance, combustion and emission characteristics were thoroughly investigated.

2. Materials and methods

2.1. Conversion process and fuel properties

The pyrolysis plant consists of three chambers; the primary chamber, the secondary chamber and the conversion chamber, as shown in Fig. 1. The feedstock is cut into small pieces (1–2 cm^2) and then is transferred to the primary chamber through a pump. In the primary and secondary chambers the plastics are purged with carbon dioxide to ensure that no oxygen is transferred into the conversion chamber (fixed bed reactor). The reason that carbon dioxide (CO_2) is used instead of another gas, is because CO_2 is heavier than the air and push the air on the top of the chamber while the feed is transferred from the bottom of the chamber to the next chamber. The fast pyrolysis takes place in the conversion chamber which is maintained at a temperature of 900 °C (heating is provided by burning natural gas) and the plastics are converted into char and gas. There are two exits from the conversion chamber; one is where the char is collected for disposal (approximately 10% of the feed) and one for the gas. The gas is passed into a condenser, where it is cooled, and pyrolysis oil is separated out. Finally, the oil is filtered to 1 μm to ensure that no deposits will be passed to the diesel engine's fuel lines and injection system. The feedstock is a composite plastic mainly made of styrene butadiene and polyester type of plastics. Table 1 shows the composition of the feedstock which fluctuates in a small scale. In general, for the production of 1 litre of PPO, 2 kg of waste plastic feedstock is required.

The elevated temperature in the conversion chamber results in a significant amount of gaseous phase product. More specifically, 30–35% of energy output is in gaseous phase while the 60–65% in liquid phase (PPO). The produced gas mainly consists of methane, hydrogen, nitrogen, CO and CO_2. Table 2 shows the average composition of the gases produced by the pyrolysis of the plastic. The gases were analysed by using the Gas Chromatography-Thermal Conductivity Detector (GC-TCD) and Gas Chromatography-Mass Spectrometry (GC-MS) methods. Due to the high amount of inert gases into the produced gas the Lower Heating Value (LHV) is low (17.68 MJ/nm^3). This is just half of the value for natural gas.

The produced oil has a dark brown almost black colour with a strong acrid smell. The GC-MS method was used to identify the most abundant compounds of the produced oil (Table 3). The GC-MS analysis showed that the oil contains a complex mixture of hydrocarbon compounds (more than 50 other compounds) which are present in lower concentrations than the presented in Table 3.

The basic properties of PPO benchmarked with diesel and the test methods which were used to determine them are presented in Table 4. Viscosity, flash point and hydrogen content of PPO are lower in comparison with diesel, while the carbon content is comparable. On the other hand, density, carbon residue, oxygen, total aromatic hydrocarbons and nitrogen content are significantly higher. LHV of PPO is marginally lower than diesel but higher than most

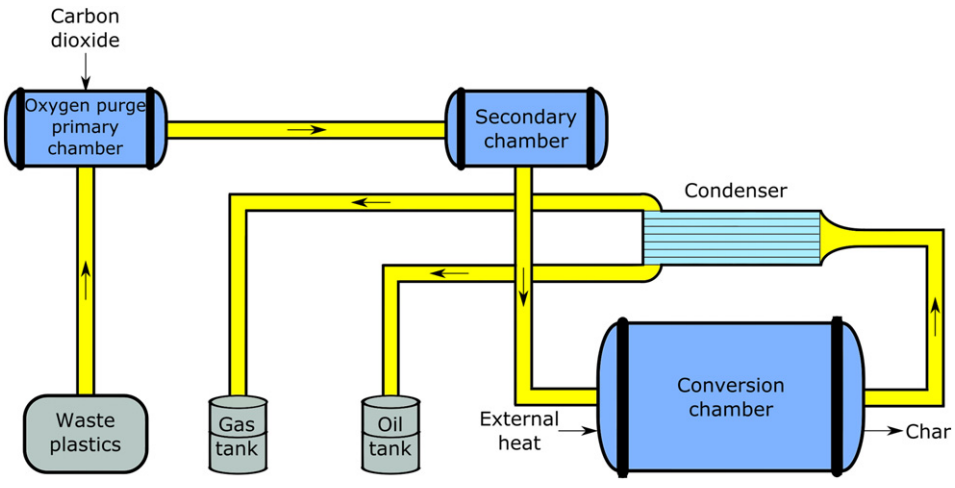

Fig. 1. Schematic layout of the pyrolysis process.

Table 1
Feedstock composition.

Material	Quantity (%wt)
Styrene butadiene	47
Polyester	26
Clay	12
Ethylene-vinyl acetate	7
Rosin	6
Polyethylene	1
Polypropylene	1

biodiesels, which indicates a good potential of this fuel candidate. The distillation test could not be performed as during the test, vapours in the sample were interfering with the level follower giving false readings. This also interferes with the heating rates etc. which caused the sample to "bump" which again would lead to false readings. In the end it was decided that the test could not safely perform. Moreover, the cetane index is calculated based on the fuel's distillation range and density, so without the distillation values it was impossible to calculate it. However, PPO has significantly higher density than diesel which indicates that the cetane index is lower. Finally, literature review reveals that the cetane number of PPO is lower than diesel [10,15,16]. According to these properties, it seems that the PPO without any substantial upgrading is most likely to be used in power generation and marine applications rather than for road transportation applications, where a much higher fuel standard is required. On this basis, the task in the present work was focused on stationary power generation using a diesel engine.

2.2. Experimental setup

The engine that was used for the experiment is a four-cylinder, direct injection, turbocharged water-cooled diesel engine. The specifications of the engine are shown in Table 5. The schematic layout of the experimental setup is given in Fig. 2. The engine is mated to an alternator and then to a load bank to control the load of the engine. The resistive load bank has a cooling fan, maximum load 72 kW and operates at 400 V – 50 Hz.

The cylinder pressure was measured by a KISTLER 6125C piezoelectric pressure transducer which was installed in the cylinder (no.1) head. The pressure transducer was connected to a KISTLER 5041E charge amplifier. For the engine's crankangle detection a KISTLER 2614C crank angle encoder was used. The encoder was placed on the crankshaft on the cylinder no.1 side.

The fuel consumption was measured by using two volumetric flow-meters, one in the supply line and one in the return line. The fuel temperature in the return line is higher (5–10 °C), which causes a considerable difference in fuel density. In order to avoid the error from the volumetric difference between the supply and the return line, two thermocouples were positioned to measure the temperature and calculate the density from the density-temperature curves.

Table 2
Produced gas composition.

Component	Quantity (v/v%)
Methane	34
Hydrogen	20
Nitrogen	17.5
Carbon monoxide	13
Carbon dioxide	11
Ethylene	3
Oxygen	1.5

Table 3
Produced oil composition.

Compound	Quantity (wt.%)
Benzene	5.3
Substituted naphthalenes	4.1
Cyclopentene	2.9
Chlorinated phenols	4.2
Cyclobutene	0.9
Naphthalene	3.7
Substituted benzenes	1.0
Cresols	3.9
Xylene	8.8
Toluene	2.7

Several more thermocouples were used to monitor the engine performance. More specifically, the measured temperatures were; air intake, air after intercooler, oil sump, coolant, exhaust in each cylinder manifold and exhaust after turbo-charger. In addition, a pressure transducer was installed after the turbo-charger to monitor the pressure during the engine operation at different loads. Finally, a Testo 350 gas analyser was used to measure the engine's exhaust emissions. Table 6 summaries the measuring ranges, accuracies and uncertainties of the instruments.

The experiments were conducted at the rated engine speed of 1500 rpm and four different loads, namely 25%, 50%, 75% and 100% of rated power which represent 3.16 bar, 6.31 bar, 9.47 bar and 12.63 bar of BMEP respectively. Five blending ratios of PPO and diesel, namely 25%, 50%, 75%, 90% and 100% (v/v%) were tested at each load. They are designated as PPO 25 to PPO 100 in the following text. During the test, the engine was started firstly on diesel and switched to PPO after 30 min when all the conditions such as coolant and oil temperatures were stabilised. All the data were collected five minutes after the engine was set on the desired power output and fuel blend conditions. More specifically, the in-cylinder pressure data was taken for 100 consecutive cycles while the flow-meter measurements, temperatures, manifold pressure and emissions were taken for a period of five minutes with one reading per second and the average values were calculated. At the end of each test, the engine was switched back to diesel and run for 30 min in order to flush out the fuel lines and the injection system.

3. Results and discussion

In this section are presented and discussed the experimental results obtained from the engine by running on PPO 25, PPO 50, PPO 75, PPO 90 and PPO 100. The blends results are compared with the

Table 4
PPO and diesel properties.

Property	Method	PPO	Diesel
Density @15 °C (kg/l)	ASTM D4052	0.9813	0.8398
Kinematic viscosity @40 °C (cSt)	IP 71	1.918	2.62
Flash point (°C)	ASTM D93	13	59.5
Aromatic content (%)	IP 391	65.5	29.5
Acid number (mg KOH/g)	IP 139	41	0
LHV (MJ/kg)	ASTM D240	38.3	42.9
Water content (mg/kg)	ASTM D6304	1190	65
Ash content (wt.%)	IP 391	0.166	<0.001
Carbon residue (wt.%)	ASTM D4530	4.83	<0.01
Hydrogen content (wt.%)	ASTM D5291	8.5	13.38
Carbon content (wt.%)	ASTM D5291	87.9	86.57
Oxygen content (wt.%)	ASTM D5622	3.3	0.05
Sulphur content (wt.%)	ASTM D5453	0.155	0.0014
Nitrogen content (mg/kg)	ASTM D4629	820	44

Table 5
Test engine specifications.

Brand	AKSA
Model	A4CRX46TI
Number of cylinders	4
Compression ratio	17:1
Displacement	4.58 lt
Rated power	68 kW
Rated speed	1500 rpm
Injection pressure	240 bar
Bore	110 mm
Stroke	125 mm

diesel fuel operation. The investigation is focused on the combustion characteristics, engine performance and exhaust emission analysis.

3.1. Combustion characteristics

Fig. 3 shows the cylinder pressure at full and 75% load. It can be seen from Fig. 3a that all the blends including PPO 100 have similar pressure profiles to diesel at full load. Marginal delay and slightly higher peak pressure are observed when PPO 100 was used however the difference was considered insignificant. Fig. 3b depicts longer delays especially for the PPO 90 and PPO 100 at 75% load. The ignition delay was even longer especially in the high PPO percentage blends resulting in unstable combustion and engine performance below 75% engine load. More specifically, the engine was unable to run on PPO 100 at 50% load and on PPO 90 at 25% load. This is possibly caused by the lower cetane number and the much higher ratio of aromatics of PPO [13]. The coefficient of variation of IMEP (COV_{IMEP}) which expresses the combustion stability of the engine was calculated in the case of PPO100 at 50% load and found to be 64 while the values on diesel operation for the specific engine are lower than 1.5.

Fig. 4 shows the cylinder peak pressure at different loads for the tested blends. The results suggest that low blending ratio (PPO 25) makes negligible effect on peak pressure regardless the engine operational conditions, but higher blending ratios in general elevated the peak pressure except at relatively low engine load. It is believed that this attributes to the combined effect of lower cetane number and lower viscosity of PPO fuel in comparison with diesel. The lower viscosity of PPO will likely improve the spray atomisation and evaporation, which will increase the portion of premixed combustion. The lower cetane number results in delayed combustion which further enlarges the premixed combustion portion. Therefore at low engine load, when PPO blends were used, the peak pressure occurred after TDC with lower values due to the prolonged combustion delay. But at high engine load, the higher portion of premixed combustion resulted in more violent combustion and higher peak pressure. This hypothesis can be supported by the heat release rate analysis and engine emissions which will be discussed later.

The heat release rate (HRR) for diesel and PPO blends at full and 75% load is presented in Fig. 5. It can be clearly seen that the higher PPO blend ratio leads to longer ignition delay and shorter combustion period. The longer ignition delay contributes to the better fuel atomisation and fuel-air mixing by allowing longer air fuel mixing time which will reduce the local rich-fuel zones where the equivalence ratio (ϕ) is greater than 1. As shown in Fig. 4a the HRR of the PPO 25 and PPO 50 is almost identical with diesel, possibly because the large portion of diesel initiates and dominates the combustion process. When the ratio of PPO increases to and above 75%, the ignition delay was significantly prolonged and a clear premixed combustion phase can be observed. At lower load of 75%, the effect of longer ignition delay for medium to high blending ratios was even more significant. The longer delay period is the main reason for the elevated HRR values of the PPO blends. Fuels with high aromatic content as PPO tend to have higher adiabatic flame temperature because of the ring structure. The high adiabatic flame temperature results in higher heat release rate [17,18]. The lower viscosity of the PPO enhances the atomisation resulting in increased HRR values [19]. Another reason which may contribute in the high HRR of PPO blends is the oxygen

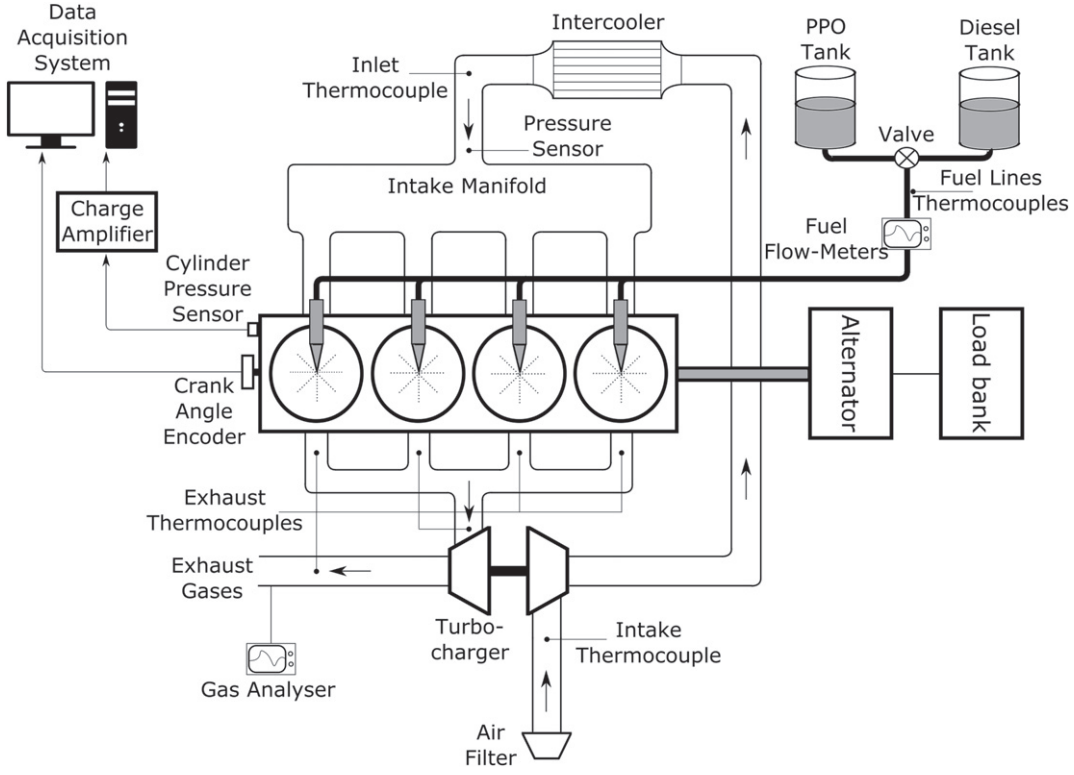

Fig. 2. Schematic layout of the experimental setup.

Table 6
Measuring ranges and accuracies of the instruments.

Instrument	Range	Accuracy
Gas analyser		
CO	0–10,000 ppm	±10 < 200 ppm
CO_2	0–50 vol.%	±0.3 < 25 vol.%
NO	0–3000 ppm	±5% reading
NO_2	0–500 ppm	±5 < 100 ppm
HC	0–40,000 ppm	±400 < 4000 ppm
Fuel flow-meters	2–100 l	±0.2%
Thermocouple Type K	0–1100 °C	±1 °C
Loadbank	0–72 kW	±0.5
Pressure transducer	0–250 bar	<±0.02 FSO
Crank angle encoder	720 × 0.5 °CA	0.5 °CA

content (3.3 wt.%) in the PPO [13]. The oxygen reduces the cylinders equivalence ratio and improves the combustion process. According to the results, PPO 100 would not be preferable for long term use due to the much higher heat release rate and more volatile combustion, which may have catastrophic effects on the engine.

3.2. Engine performance

Fig. 6 depicts the brake specific fuel consumption (BSFC) and the brake thermal efficiency (BTE) of the fuel blends at different loads. The BSFC of the blends increases considerably at all operational conditions, even with the lowest blending ratio. This can be partly attributed to the lower heating value of PPO fuel. However, the lower BTE shown indicates that the engine operates less efficiently when PPO is used regardless of the blending ratio. The lower BTE of PPO blends can be explained by the existence of a high amount of aromatics contained in PPO, because the aromatic bonds require more energy to break [20]. Another reason could be that the higher combustion temperature of PPO results in high heat transfer losses. Nevertheless, one should notice from Fig. 6 that the fuel consumption and thermal efficiency do not deteriorate much further with increased blending ratio and the efficiency is only marginally lower than that of diesel at medium load. These results suggest some potential working conditions for effectively utilising this fuel candidate.

Fig. 7 depicts the variation of exhaust gas temperature with load for diesel and PPO blends. It can be seen that the exhaust gas temperature for diesel is lower at all loads and that the exhaust temperature marginally increase as the PPO blending ratio increases. In the case of diesel operation, the exhaust gas temperature varies from 267 °C at 25% load to 478 °C at full load, whereas for the PPO 100 ranges from 290 °C at 25% load to 488 °C at rated power. This trend can be explained by the prolonged ignition delay period. Nevertheless, the effect on exhaust gas temperature is deemed insignificant.

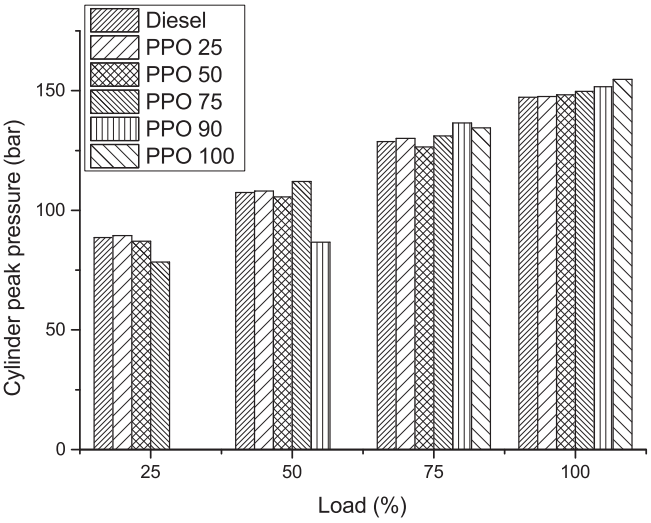

Fig. 4. Variation of cylinder peak pressure with load.

3.3. Exhaust emissions

The variation of nitrogen oxides (NO_X) with brake power for diesel and PPO blends is shown in Fig. 8. Three NO_X production mechanisms exist in combustion theory; the thermal mechanism, the prompt mechanism and the fuel mechanism [17,21]. In diesel engines the mechanism that produces the majority of NO_X is the thermal mechanism due to the elevated temperature and high oxygen availability. According to the experimental results presented in Fig. 8, NO_X emissions increase as the percentage of PPO increases. This is due to the longer ignition delay which results in higher portion of premixed combustion, thus higher heat release rates and higher in-cylinder temperatures. Another reason that may affect the NO_X emissions is the higher nitrogen content in the fuel that promotes the NO_X formation by fuel mechanism.

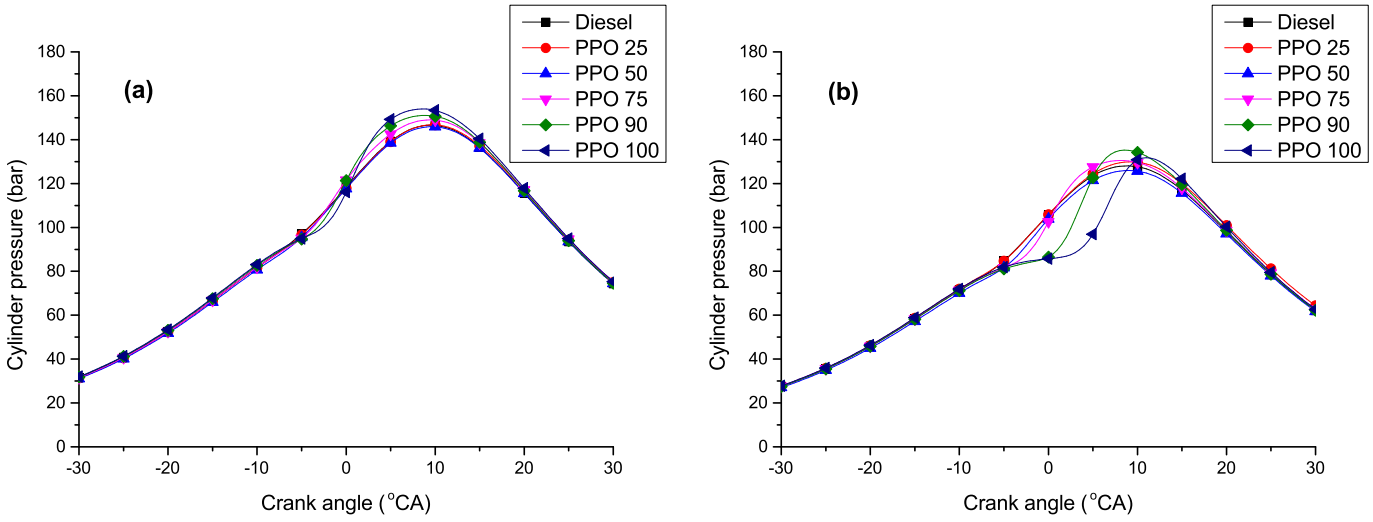

Fig. 3. Variation of cylinder pressure for 100% (a) and 75% (b) load.

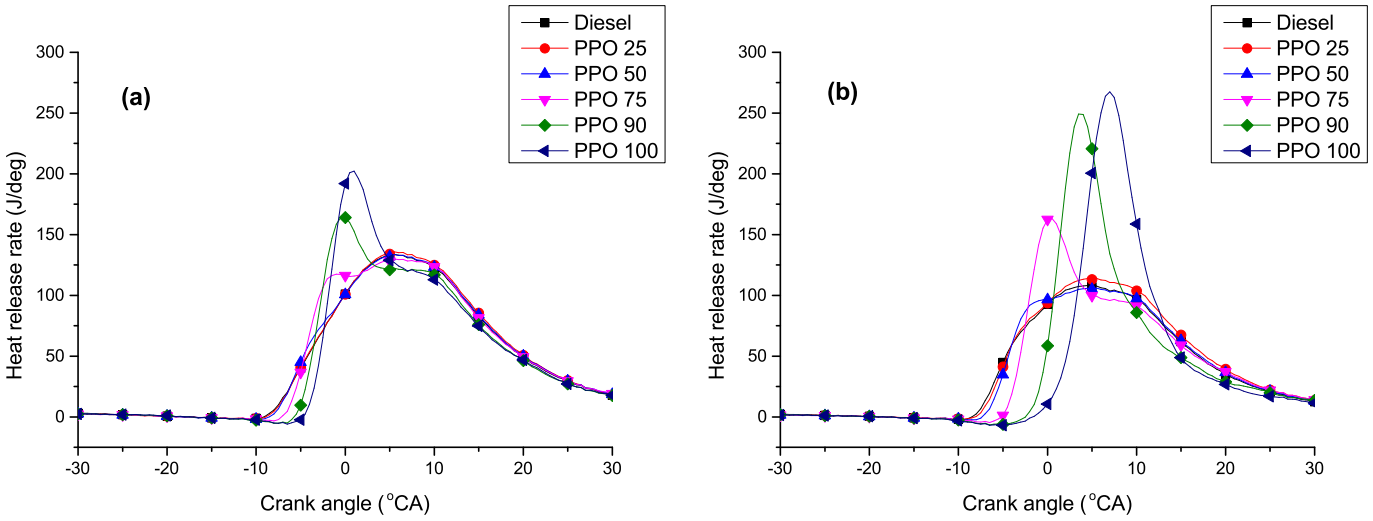

Fig. 5. Variation of heat release rate for 100% (a) and 75% (b) load.

Fig. 9 presents the variation of unburned HC emissions. The UHC emissions in the exhaust are mainly due to the under-mixing or over-leaning (bulk-quenching) zones and wall flame-quenching [17,22,23]. It can be seen that the UHC emission for diesel operation is significantly lower than that for PPO blends and the UHC emission increases as the blending ratio increases. For the same blending ratio, UHC emissions decrease with increased load, which is in line with diesel. The reason that PPO blends result in higher UHC emissions remains unrevealed, but it is believed that the higher aromatic contents may be responsible [19]. Another possible reason is that the spray of PPO blends may have better chance to impinge the wall due to its higher density, lower viscosity and cetane number which results in longer ignition delay. The spray test of the PPO fuel is being undertaken to provide additional information. The result will be published in our future publications.

Fig. 10 shows the variation of carbon monoxide (CO) emissions. CO emissions are mainly formed by incomplete combustion and affected by the equivalence ratio and temperature. It can be observed from the experimental results that the CO emissions decrease as the engine load increase regardless of the fuel. In general, higher PPO blending ratio results in higher CO emissions, particularly for high blending ratios over 75% (inclusive) at low loads. This result indicates severe deterioration of combustion at these operational conditions, possibly due to the low cetane number of PPO, which can also be observed from the lower in-cylinder peak pressure. Interestingly, the incomplete oxidation at these conditions does not have a significant impact on engine thermal efficiency. Nevertheless, when low to medium blending ratio fuel was used, or when the engine operates at high load, the increase of CO emissions is marginal and should not have any practical implication.

Carbon dioxide (CO_2) emission is a result of complete combustion where the carbon atoms contained in the fuel are fully oxidized. It is usually not regulated by emission legislations and not considered a harmful gas, however since it is a greenhouse gas, there is a strong requirement to reduce CO_2 emissions. Fig. 11 presents the variation of CO_2 emissions against load for diesel and PPO blends. A nearly linear relationship between the increase in CO_2 emissions and the PPO blending ratio can be observed. This is due to the higher C:H ratio of PPO (C:H = 10.34) than that of diesel (C:H = 6.47), meaning for the same amount of energy released from combustion, more carbon

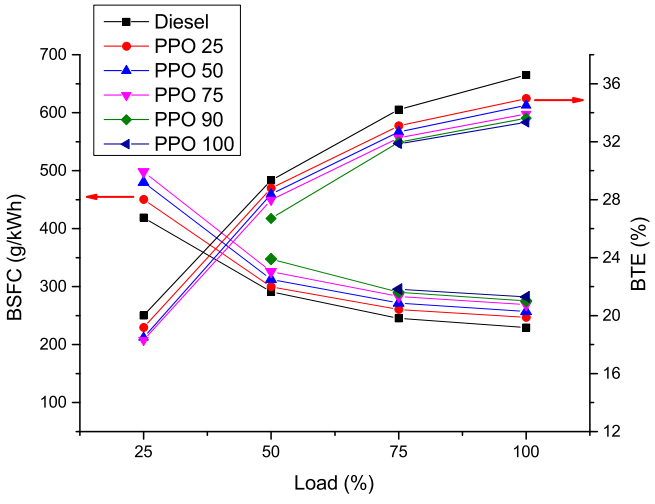

Fig. 6. Variation of BSFC and BTE with load.

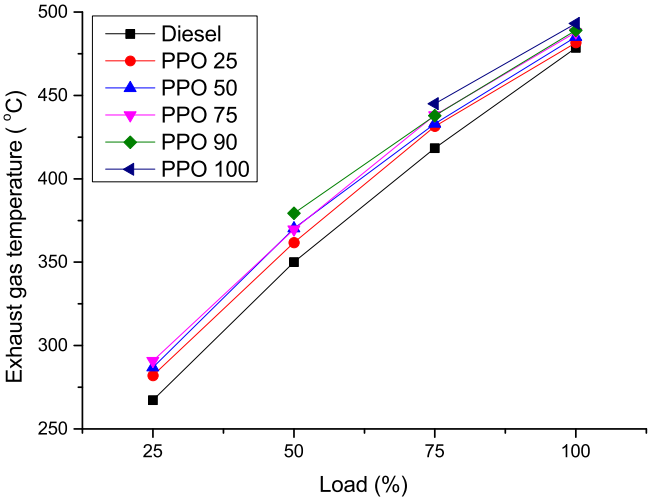

Fig. 7. Variation of exhaust gas temperature with load.

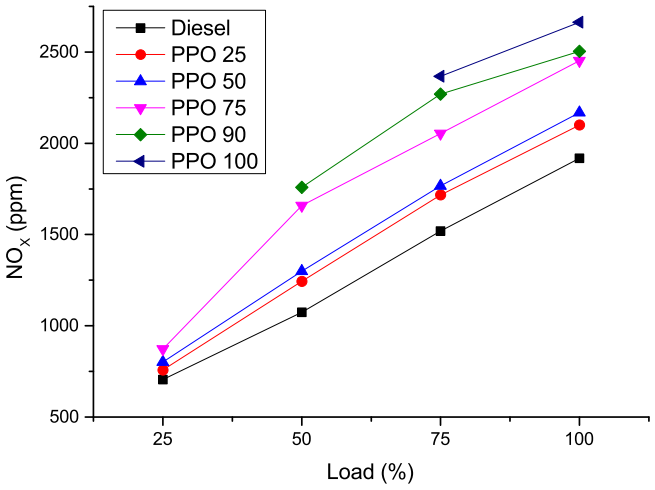

Fig. 8. Variation of oxides of nitrogen emission with load.

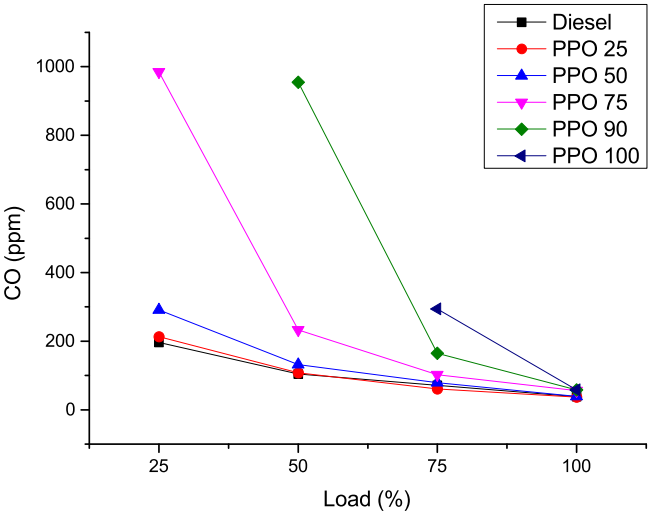

Fig. 10. Variation of carbon monoxide emission with load.

has to be oxidized and more CO_2 will be formed. This result suggests a negative environmental impact to use PPO as fuel, however this fuel is produced from waste feedstock which is otherwise landfilled. More CO_2 would be released over the long term in that case. For this reason, it is still believed that this is a promising and sustainable pathway to utilise the waste plastics.

4. Conclusions

An experimental investigation was carried out to analyse and understand the combustion, performance and emission characteristics of a diesel engine running on an oil which was derived from the pyrolysis of waste plastics. The tests were performed on a diesel engine gen-set. The blending ratio with diesel was varied from 25% to 100%. The following conclusions can be drawn from the test results:

- The engine was able to operate steadily on PPO 100 at loads higher than 75%, on PPO 90 for loads higher than 50% and on lower PPO blends for all loads.
- PPO blends have longer ignition delay, higher cylinder peak pressure and higher heat release rate due to the lower cetane number.
- The engine thermal efficiency decreased by 3–4% when PPO blends were used in comparison with diesel. But increasing PPO ratio does not have a significant impact on thermal efficiency.
- All measured emissions, including NO_X, UHC, CO and CO_2, increase with higher PPO blending ratio. For low to medium blending ratios, the increases of NO_X and CO are mild.

The testing results suggest that for the long-term running, a blend of 60% – 70% PPO operating at 80% – 90% engine load seems to have the most promising potential to achieve the best engine performance and emissions. More parameters such as injection timing, injection pressure and cetane number improvers need to be explored in order to obtain the optimum engine performance.

Acknowledgments

The authors sincerely thank Thermitech Solutions Ltd and UK Engineering and Physical Sciences Research Council (EP/K036548/2) for the support to conduct this research.

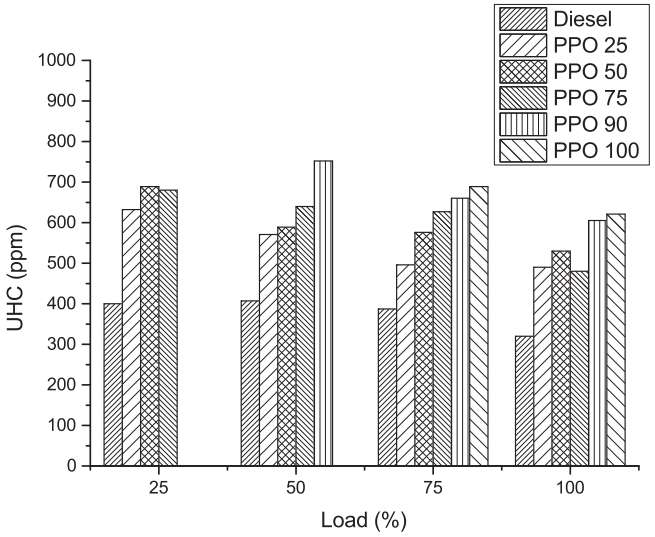

Fig. 9. Variation of unburned hydrocarbon emission with load.

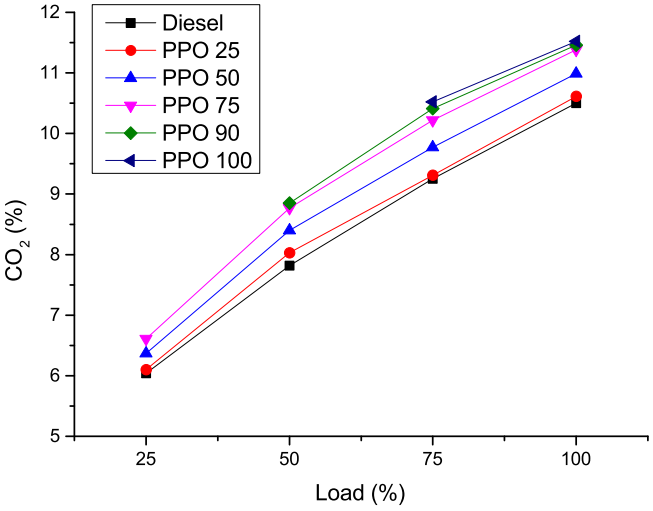

Fig. 11. Variation of carbon dioxide emission with load.

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